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AN ANALYSIS OF B-1B EXTERIOR JET BLAST WINDSHIELD ANTI-ICING PERFORMANCE USING PRE-COOLED COMPRESSOR BLEED AIR

D.S. EMMER
M.P. BOUCHARD

UNIVERSITY OF DAYTON RESEARCH INSTITUTE
300 COLLEGE PARK
DAYTON OH 45469-0110

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ERIK W. JOY, 1Lt, USAF
B-1B Project Engineer
Windshield Program Office

COLLEEN A. JASPER, Capt, USAF
Chief, Windshield Program Office

RICHARD E. COLCLOUGH, JR.
Chief
Vehicle Subsystems Division

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D. S. Emmer
M. P. Bouchard

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Aerospace Mechanics Division
300 College Park
Dayton, Ohio 45469-0110

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This work presents the results of an analytical study designed to evaluate whether the B-1B hot-air windshield de-icing/anti-icing system, operating independently from the embedded electrical resistance system, was capable of adequately meeting de-icing and anti-icing requirements. Two icing scenarios were considered in loiter, landing and ground/taxi modes of operation. The results indicate that in a loiter and landing mode, the system capability ranges from marginal to adequate. Additional work is needed to expand the applicability of the analysis mode to ground/taxi conditions.

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NOMENCLATURE

D	Median Droplet Diameter, microns
K_1,K_2	Constants
LWC	Liquid Water Content, gm/cu. meter
P	Pressure, lb/sq. ft.
T	Temperature, deg. R
T_w	Windshield Surface Temperature, deg. R
V	Velocity, ft/sec
W_b	Bleed Air Mass Flow Rate, lb/sec
X	Distance Along Windshield, ft.

Subscripts

a	Ambient
b	Bleed Air
D	Droplet
L	Liquid Water Content
0	Dry Air

FOREWORD

This study was performed by the Aerospace Mechanics Division of the University of Dayton Research Institute (UDRI), Dayton, Ohio. The work was sponsored by the United States Air Force under contract number F33615-92-C-3400. The Air Force contract monitor was Lt. Erik Joy, WL/FIVR, Wright-Patterson AFB, Dayton, Ohio.

The work was conducted during the period from March, 1994, to May, 1994. UDRI supervision was provided by Mr. Blaine S. West, Head, Aerospace Mechanics Division, Mr. Gregory J. Stenger, Structures Group Leader, Mr. Michael P. Bouchard, Project Leader and Dr. Deems S. Emmer, Principal Investigator.

SECTION 1
INTRODUCTION

A significant body of research has been documented relative to the design and performance of aircraft windshield de-icing and anti-icing systems (Ref. 1). Over the years various icing control methods have been employed that include internal and external hot-air blast, electrical resistance heating utilizing embedded electrical wires or electrical conducting films, infrared radiation, aerodynamic heating and others. While de-icing equipment is designed to remove ice accretion that has formed or is forming, anti-icing equipment is designed to prevent the initial formation of ice on the aircraft surfaces. The effectiveness, level of performance and method of selection of any one of the above de-icing or anti-icing methods, as applied to any particular aircraft, varies widely and has been demonstrated to be especially sensitive to aircraft performance, flight profile, and atmospheric icing conditions as well as the anti-icing hardware itself. Due to issues of safety as well as wide variations in application and performance requirements, most commercial and military aircraft do not rely on a single windshield anti-icing system but employ multiple systems. The most common systems combine or supplement embedded wires or transparent, electrically conductive film, with the external hot-air blast similar to the configuration found on the current production model of the B-1B.

The objective of the present study was to evaluate the performance level of the B-1B external, hot-air jet blast, windshield anti-icing system described as part of the "Environmental Protection System" or "EPS" (Ref. 2). The analysis sought to determine if the hot-air jet blast system, operating independently from the embedded electrical film system, was sufficient to meet aircraft windshield anti-icing requirements in at least two typical icing scenarios for aircraft in loiter, landing, and ground/taxi modes of operation. The analysis was restricted to an assessment of windshield heating only and did not include the anti-icing requirements of the airframe, flight surfaces, engine nacelles, radomes, probes or other major aircraft systems.

SECTION 2
PHYSICAL DESCRIPTION

2.1 Windshield Characteristics

The B-1B windshield anti-icing system, shown schematically in Figure 1, is classified as part of the overall Environmental Control System (ECS) (Ref. 3). Note that the system includes rain removal and windshield washing capabilities as well as hot-air jet blast and electrical anti-icing/de-icing components.

A typical B-1B windshield panel layout and cross section are shown in Figures 2 and 3. Two windshield configurations were considered. The current production configuration, with a total overall thickness of 1.50 inches, consists of a 5-layer laminate. The outer layer of laminate is made up of a 0.120-inch-thick layer of strengthened glass, while those that remain are alternating layers of silicone and polycarbonate. The second configuration, a proposed all-plastic panel, is similar except that the outer layer of glass is replaced with a layer of polycarbonate.

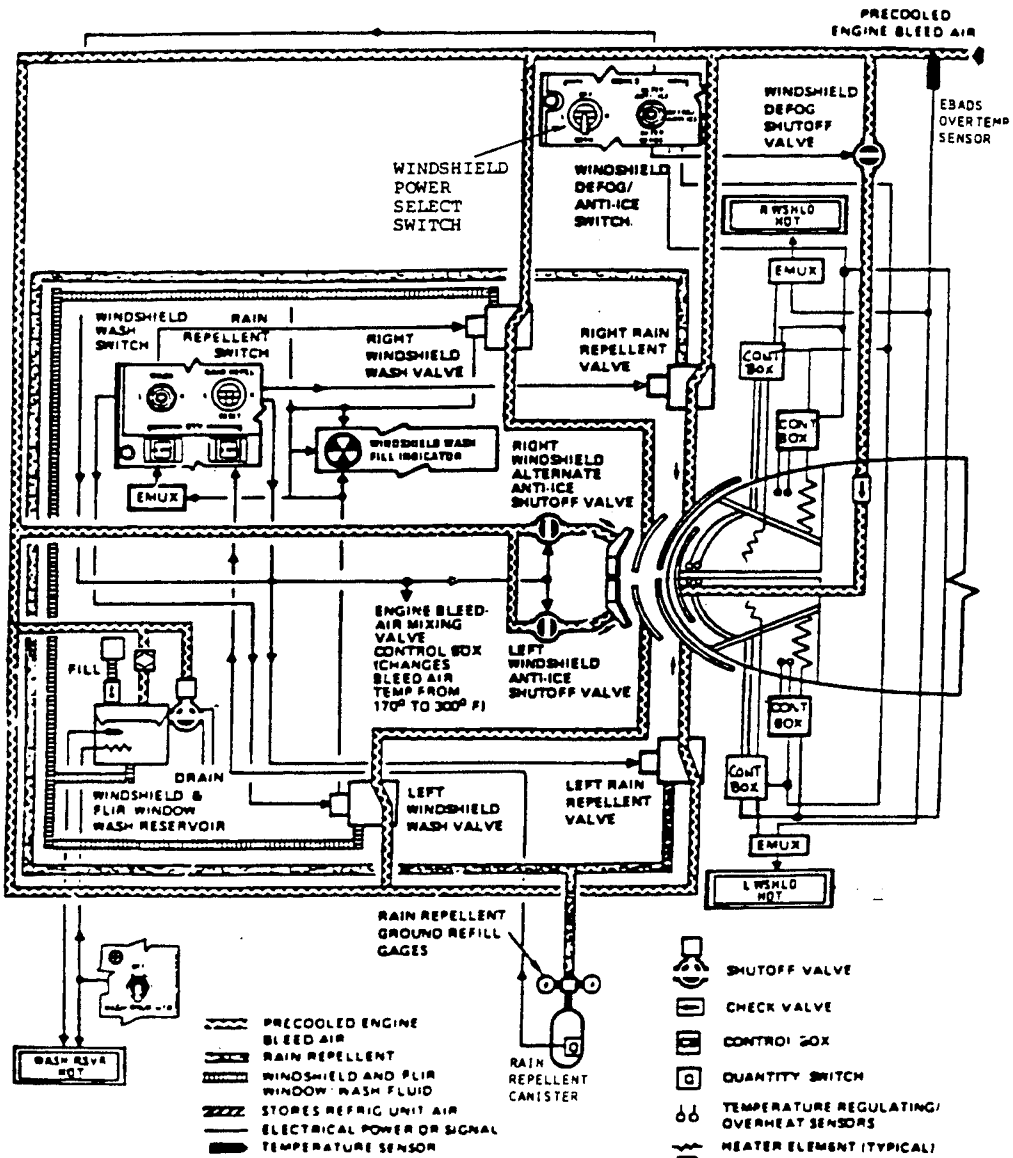

Figure 1. B-1B Environmental Protection System (EPS) (Ref. 2)

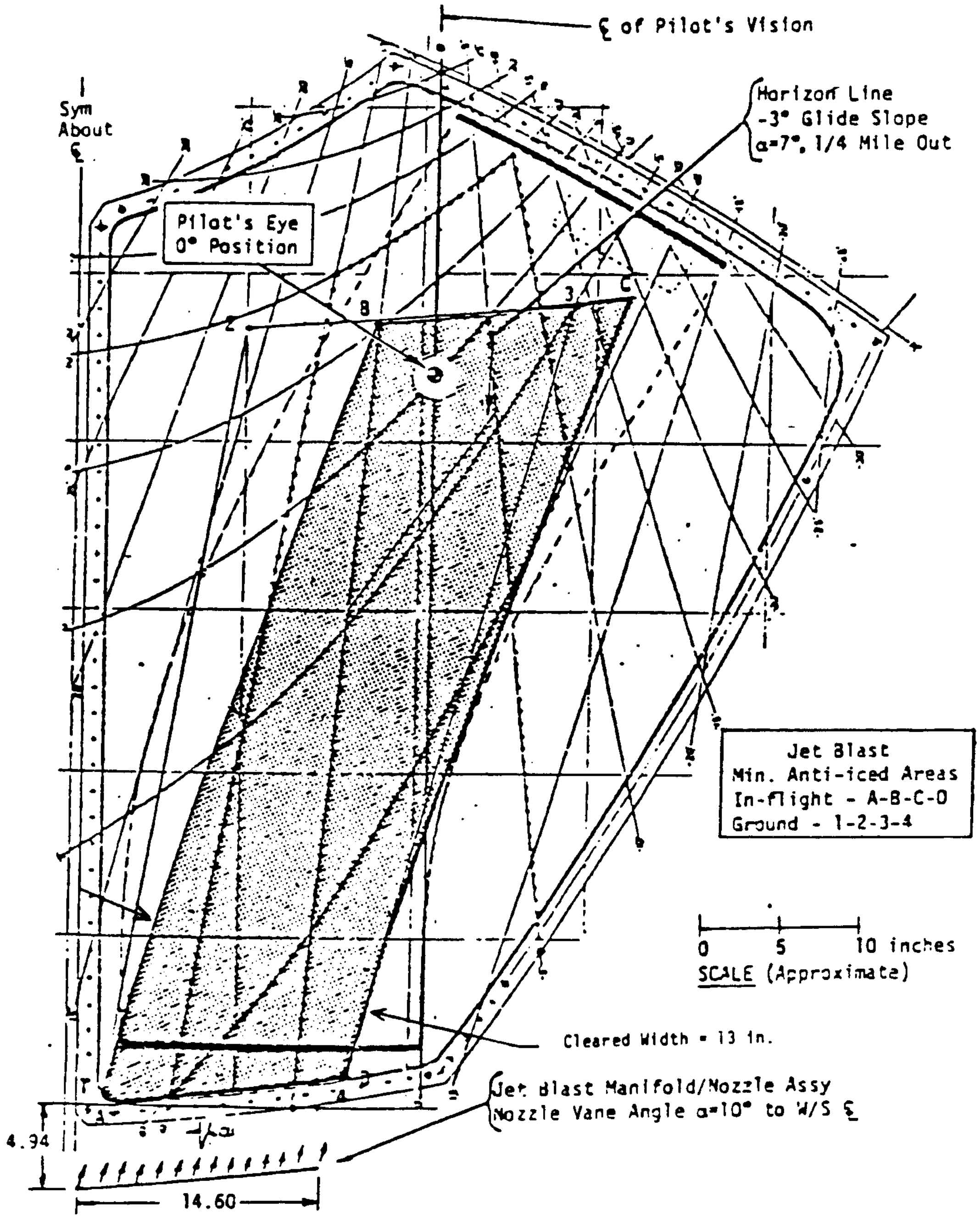

Figure 2. Windshield Panel Detail; Flat Area Pattern (Ref. 2).

The surface area subject to hot-air anti-icing is considerably smaller than the total area of the windshield surface. The total area of one side of the forward-facing windshield panel is approximately 15.35 sq. ft., while the projected frontal area is approximately 5.2 sq. ft. The area subject to hot-air anti-icing, shown shaded in Figure 2, is approximately 4.5 sq. ft. and is an area measuring approximately 13 inches wide x 50 inches long.

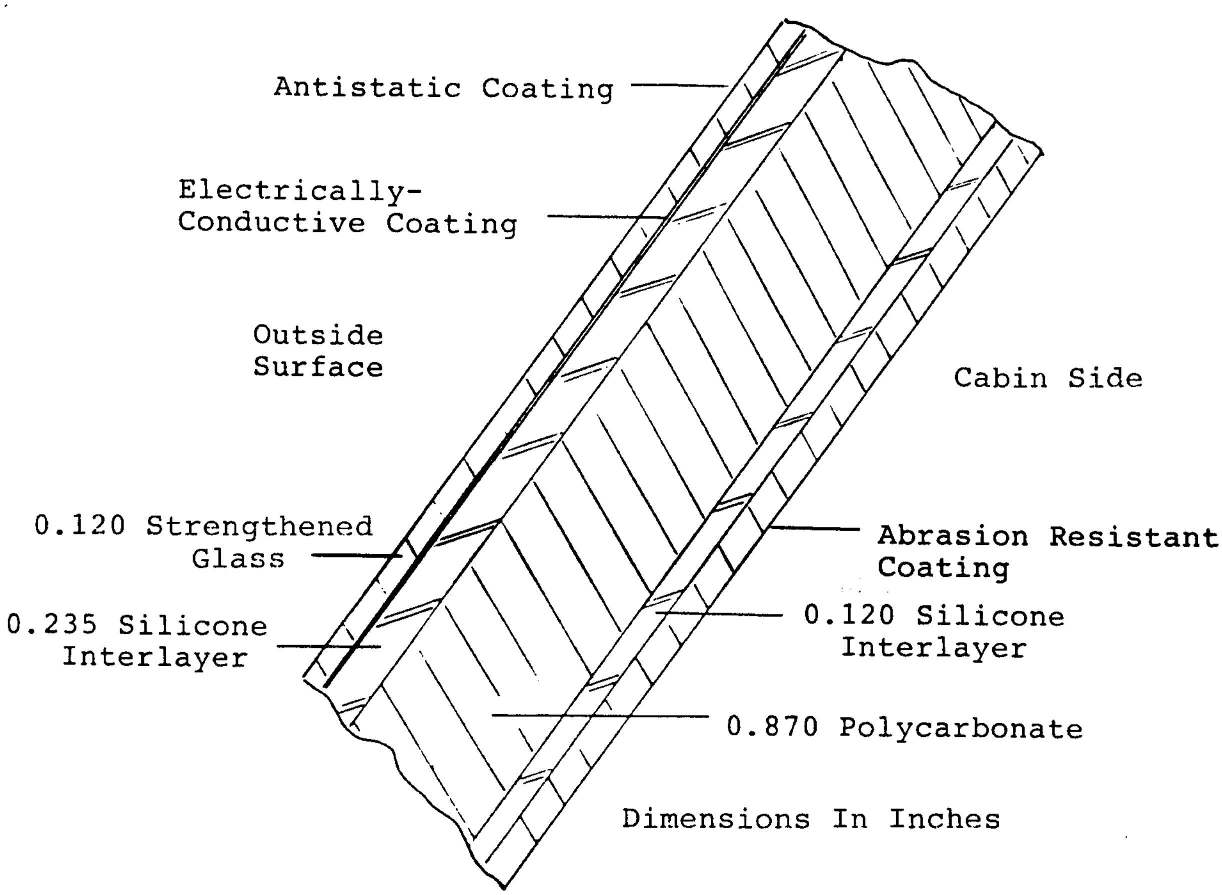

Figure 3. B-1B Windshield Cross Section (Ref. 2).

2.2 Nozzle Characteristics

The hot-air jet blast nozzles, illustrated in Figures 4 and 5, are located both internally and externally at the forward base of the windshield. Air is discharged at the base of the windshield panels and is directed upward and parallel along the windshield surface.

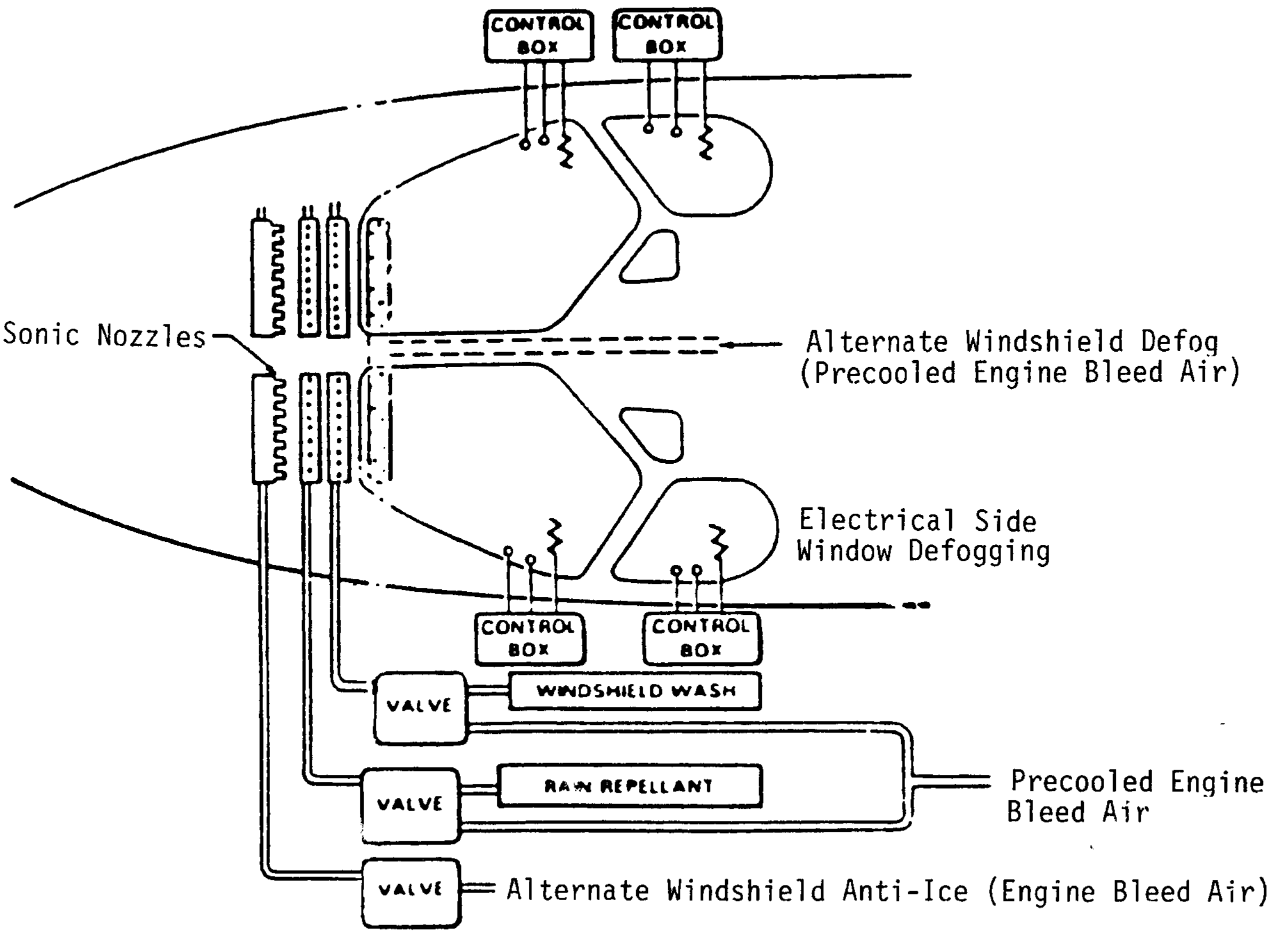

Figure 4. Windshield Nozzles; Top View (Ref.
(Ref. NA 86-1000, Vol. I)

The external nozzles are associated with the major anti-icing/de-icing functions of the windshield while the internal nozzles are responsible for defrost/defog functions. Each nozzle, one external and one internal for each of the two windshield panels, is fed by precooled engine compressor bleed air. Both internal and external nozzle exit air temperature is regulated to maximum values

of 170°F while on the ground, 300°F in flight, and a maximum pressure of 50 lb/sq.in. The external nozzle mass flow rates are maintained at 60 pounds/minute while interior nozzles are regulated to 5.5 pounds/minute (Ref. 4). The external nozzle exit openings measure 14 inches long by 0.125 inch wide giving each an exit area of 1.750 square inches. A listing of the external nozzle operating characteristics is given in Table 1.

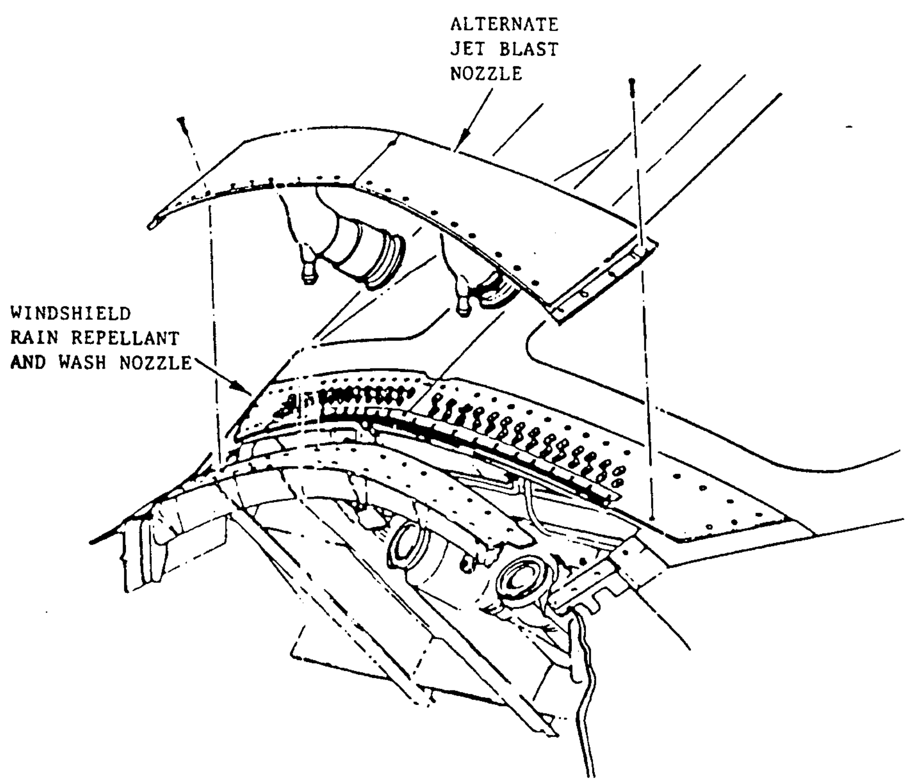

Figure 5. Anti-Ice Nozzle Geometry Detail
(Ref. NA 86-1000, Vol. I)

Table 1. External Nozzle Operating Characteristics

--- In Flight ---

Parameter	Known Value	Calculated Value
Mass flow rate, lb/min	60.0	------
Total pressure, lb/sq. in	------	34.0
Total temperature, deg. F	------	505
Exit static pressure, lb/sq. in	14.7	------
Exit static temperature, deg. F	300	------
Exit velocity, ft/sec	------	1570
Exit Mach number	------	1.16
Exit area, sq. inches	1.750	------

--- On the ground ---

Parameter	Known Value	Calculated Value
Mass flow rate, lb/min	60.0	------
Total pressure, lb/sq. in	------	30.0
Total temperature, deg. F	------	312
Exit static pressure, lb/sq. in	14.7	------
Exit static temperature, deg. F	170	------
Exit velocity, ft/sec	------	1300
Exit Mach number	------	1.06
Exit area, sq. inches	1.750	------

SECTION 3

ICING CRITERIA AND LIMITATIONS

The selection of icing parameters were based on scenarios representative of loiter, landing and ground/taxi modes of aircraft operation. For each operational mode, selection of the specific icing criteria and atmospheric conditions under which the aircraft was most likely to encounter icing, were based on a mix of known "most probable" and "worst case" variables documented by NASA, the FAA and the Air Force (Refs. 5,6,7).

In general, the aircraft windshield's susceptibility to icing is a function of many variables, which includes not only altitude and ambient temperature and pressure, but also aircraft airspeed, windshield orientation, panel geometry, water droplet diameter, liquid water content, cloud formation and relative humidity. For an aircraft utilizing hot-air jet blast anti-icing, the list of variables includes compressor bleed air temperature and bleed air mass flow rate.

Limitations on some of these parameters are discussed in References 5 and 6. Figure 6 illustrates the "most probable" icing conditions as a function of ambient temperature and altitude. Figure 7 is representative of the envelope of maximum continuous icing between 0 and 22,000 feet. The lower border of the envelope represents the "worst case" lowest ambient temperature and, therefore, the highest heating requirements, where icing might be encountered. The influence of the effects of airspeed, aerodynamic heating and altitude on the boundaries are shown in Figure 8. It is interesting to note that at altitudes above approximately 22,000 feet very little ice accretion occurs due to the decreasing liquid water content of the air with decreasing air temperature.

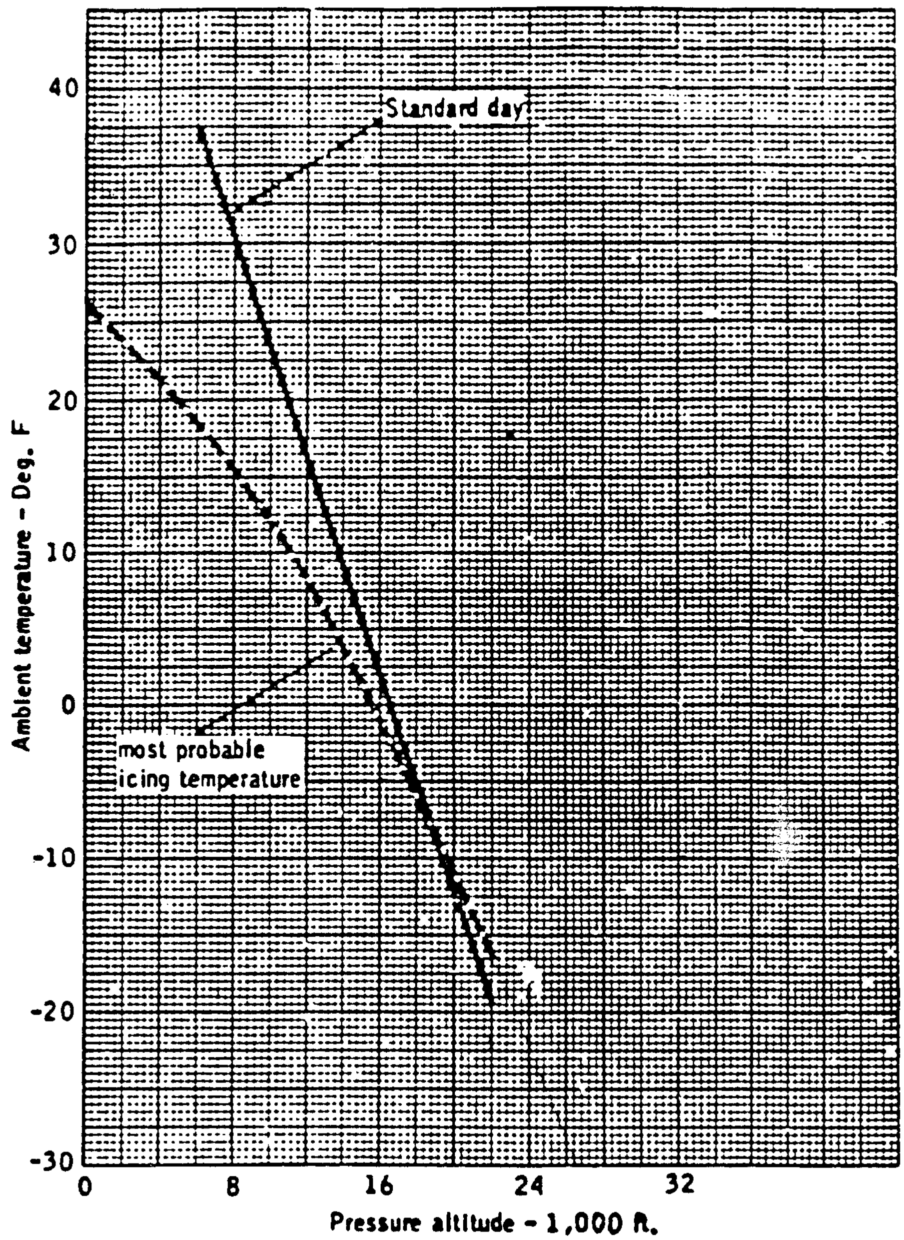

Figure 6. Most Probable Icing Temperature vs. Altitude (Ref. 5)

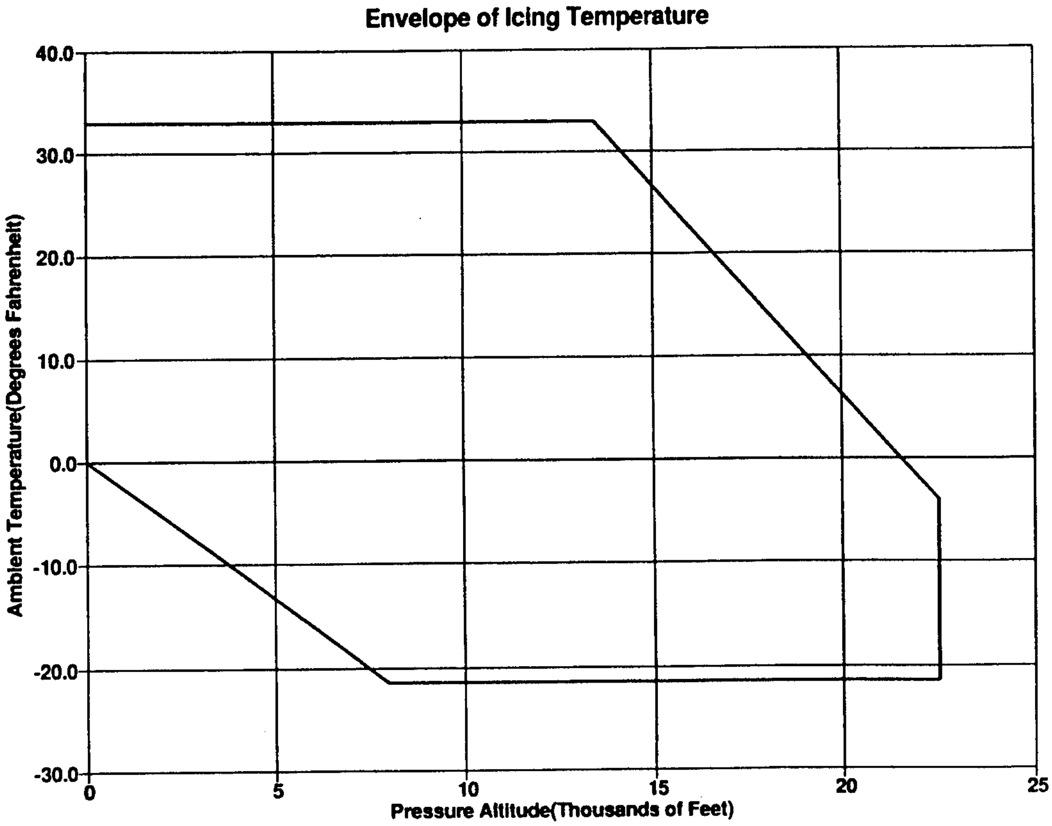

Figure 7. Maximum Continuous Icing Envelope (Ref. 2)

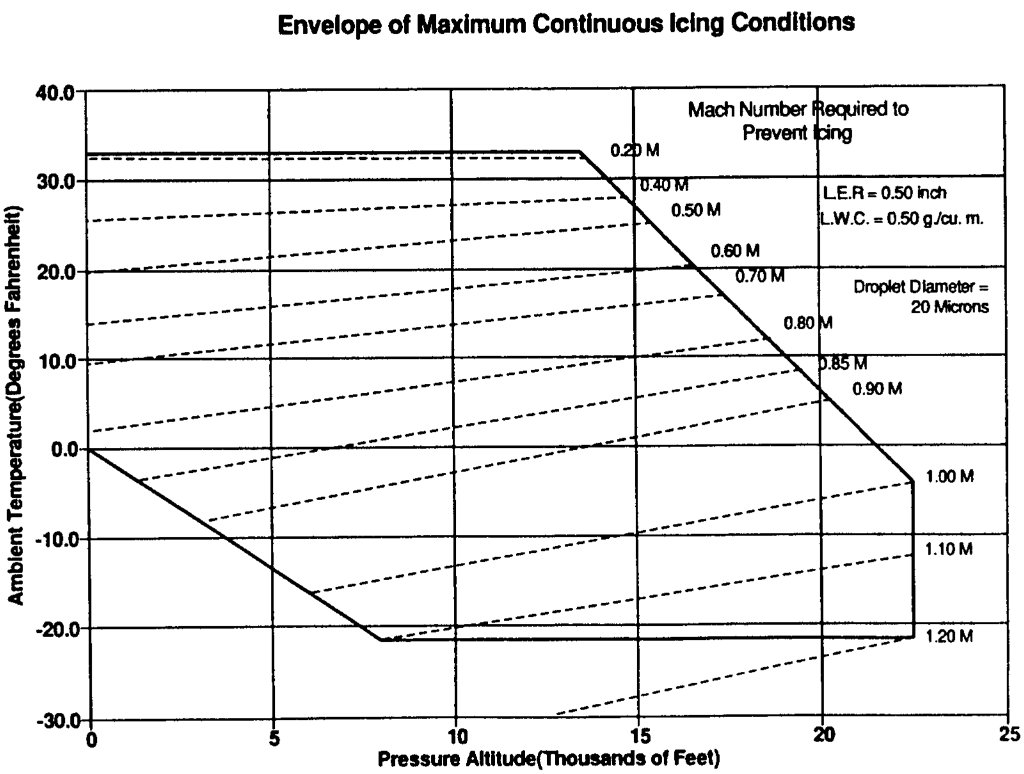

Figure 8. Mach Number Required to Prevent Icing (Ref. 2)

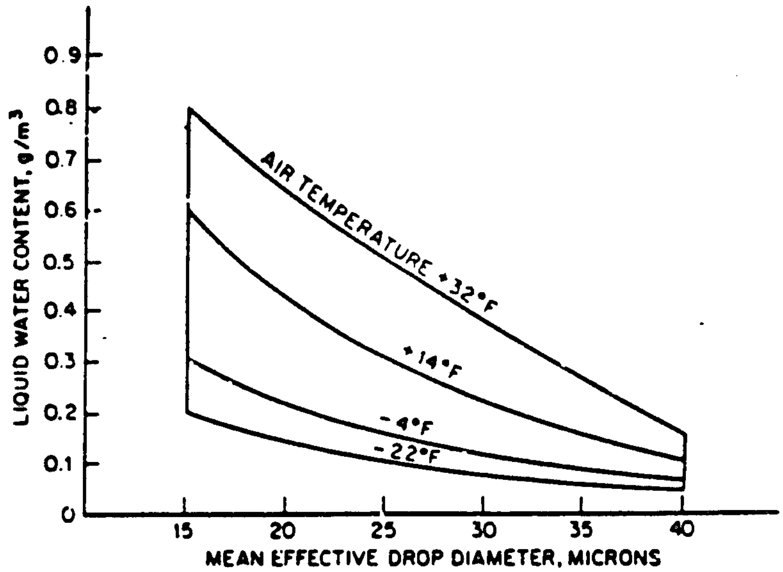

Figure 9. Liquid Water Content vs. Droplet Diameter (Ref. 2)

The relationship between liquid water content, droplet size and ambient temperature is shown in Figure 9. The icing parameters selected for use in the present analysis are listed in Tables 2 and 3. Note that the Case 1 parameters correspond to "most probable" icing conditions and Case 2 parameters correspond to a "worst case" highest heating requirement.

Table 2. Icing Parameters: Loiter

Parameter	Case 1	Case 2
Pressure altitude, ft.	4000	8000
Ambient pressure, lb/sq.ft	1828	1572
Ambient temperature, deg. F	22.0	-22.0
Airspeed, ft/sec	470	350
Mach number	0.44	0.34
Median droplet diameter, microns	20	15
Liquid water content, gm/cu. m	0.5	0.2

Table 3. Icing Parameters: Landing

Parameter	Case 1	Case 2
Pressure altitude, ft.	S.L.	S.L.
Ambient pressure, lb/sq.ft	2116	2116
Ambient temperature, deg. F	26.0	0
Airspeed, ft/sec	250	200
Mach number	0.23	0.19
Median droplet diameter, microns	20	20
Liquid water content, gm/cu. m	0.5	0.3

Table 4. Icing Parameters: Ground/Taxi

Parameter	Case 1	Case 2
Pressure altitude, ft.	S.L.	S.L.
Ambient pressure, lb/sq.ft	2116	2116
Ambient temperature, deg. F	26.0	0
Airspeed, ft/sec	25	25
Mach number	0	0
Median droplet diameter, microns	20	20
Liquid water content, gm/cu. m	0.5	0.3

SECTION 4
ANALYSIS

The objective of the present study was to provide a theoretical model suitable for predicting the temperature distribution along the surface of the windshield from the hot-air nozzle exit plane to the pilot's eye location. Following Ross (Ref. 9), the model is adaptable to either dry or icing conditions and requires only limited parametric information regarding the aircraft flight profile, atmospheric conditions and compressor bleed data. The model is empirical, its formulation being based on experimental flight test and thermocouple data taken throughout a range of icing conditions. The expression for the model is

$$\frac{T_w}{T_a} = 1 + [K_1 + K_2 \log_{10}(W_b V / X^2 P_a)] \times \left(\frac{T_b}{T_a} - 1\right) \tag{1}$$

where T_w is the windshield surface temperature in degrees R, T_a is ambient temperature in degrees R, W_b is bleed air mass flow rate in lb/sec, V is aircraft airspeed in ft/sec, X is distance along the windshield from the nozzle exit plane in feet, P_a is ambient pressure in lb/sq. ft., and T_b is bleed air temperature in degrees R.

The constants, K_1 and K_2, are experimentally determined. Their general form is given by

$$K_1 = K_{1_0} + K_{1_D} + K_{1_L} \tag{2}$$

and

$$K_2 = K_{2_0} + K_{2_D} + K_{2_L} \tag{3}$$

where the "0" term is the dry air term, the "D" term accounts for median droplet diameter and the "L" term accounts for the liquid water content. For dry air conditions, the "D" and "L" terms are numerically zero. The variations of K_1 and K_2 values with droplet size and liquid water content are shown in Figures 10 and 11.

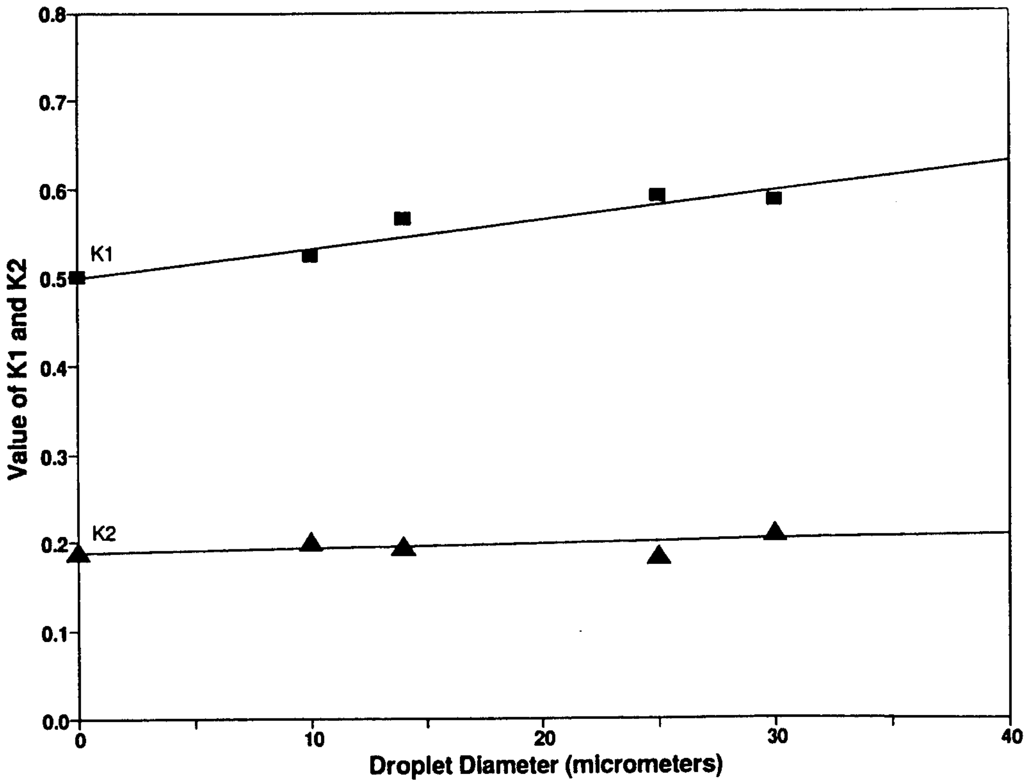

Figure 10. Variations of K_1 and K_2 with Droplet Diameter (Ref. 9)

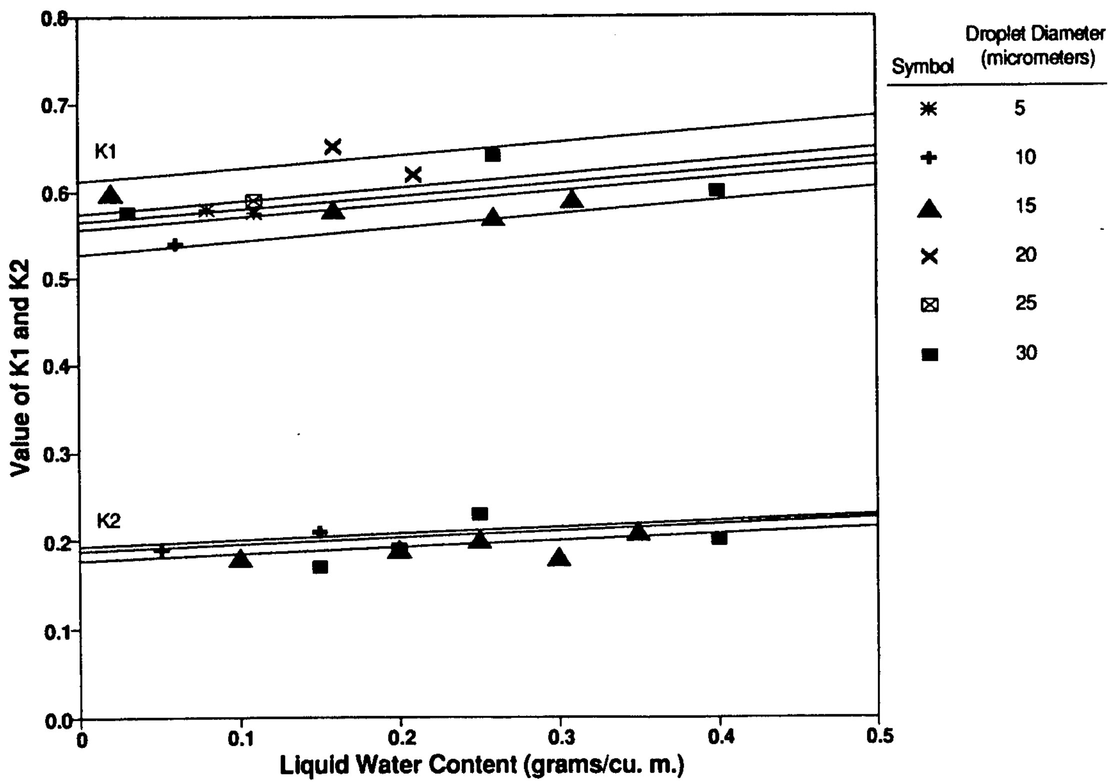

Figure 11. Variations of K_1 and K_2 with Liquid Water Content (Ref. 9)

Following Ross's linear regression analysis of his original flight test data (Ref.(9), the values of the constants were determined to be given by the following expressions

$$K_1=0.5131+0.003135(D)+0.06808(LWC) \tag{4}$$

and

$$K_2=0.1902+0.003793(D)+0.003974(LWC) \tag{5}$$

SECTION 5
RESULTS AND DISCUSSION

The calculated windshield temperature distributions, based on the input data listed in Tables 1, 2, and 3, are shown in Figures 12 and 13. The distributions apply to both the glass and plastic surfaced windshields. Also shown on the plots are the locations (relative to the nozzle) of the windshield forward edge, the intercept of the pilot's horizontal line of sight and the windshield (design eye intercept, 4.18 ft from nozzle - Figure 2), and the 35°F cutoff line. For the purposes of this evaluation, the analysis considers the windshield to be ice free as long as the surface temperature is predicted to remain above 35°F, the limiting value suggested in Reference 10. At 35°F or above, ice would not form and any existing ice accumulation would melt. Therefore, a clear windshield would be indicated in Figures 12 and 13 by a plotted curve lying completely above the 35°F line in the region between the windshield forward edge and the pilot's design eye intercept.

In all cases, the nozzle air temperature is predicted to rapidly decrease within a very short distance downstream of the nozzle exit. This decrease is attributable to the extreme effects of mixing and diffusion of the heated nozzle air with the free stream flow field.

For the loiter and landing modes of operation, the performance of the hot-air jet blast anti-icing system is indicated to be from marginal to adequate. The windshield is cleared (out to 5.69 ft) or nearly cleared (out to 4.1 ft) for the Loiter: Case 1 and Landing: Case 1 conditions, respectively. The reduced aircraft airspeed and ambient temperature for Loiter: Case 2 and Landing: Case 2 reduced the cleared length to 2.98 ft and 2.43 ft, respectively. The analysis tends to be conservative (i.e., the cleared area is generally larger than computed),[9] and is somewhat approximate for aircraft other than the business jet from which the values of the constants K_1 and K_2 in Equations (4) and (5) were derived. Therefore the results presented in Figures 12 and 13 represent conservative first approximations to the actual performance of the B-1B blown air deice system.

Application of Equation 1 to the ground/taxi cases resulted in unrealistically low windshield surface temperatures and, therefore, only small, localized, deiced zones near the bleed air nozzle. Discussion with R. Ross ascertained that the equation had not been validated

ground/taxi conditions, having been developed based solely on flight test data. Results for the ground/taxi cases therefore are not presented in this report.

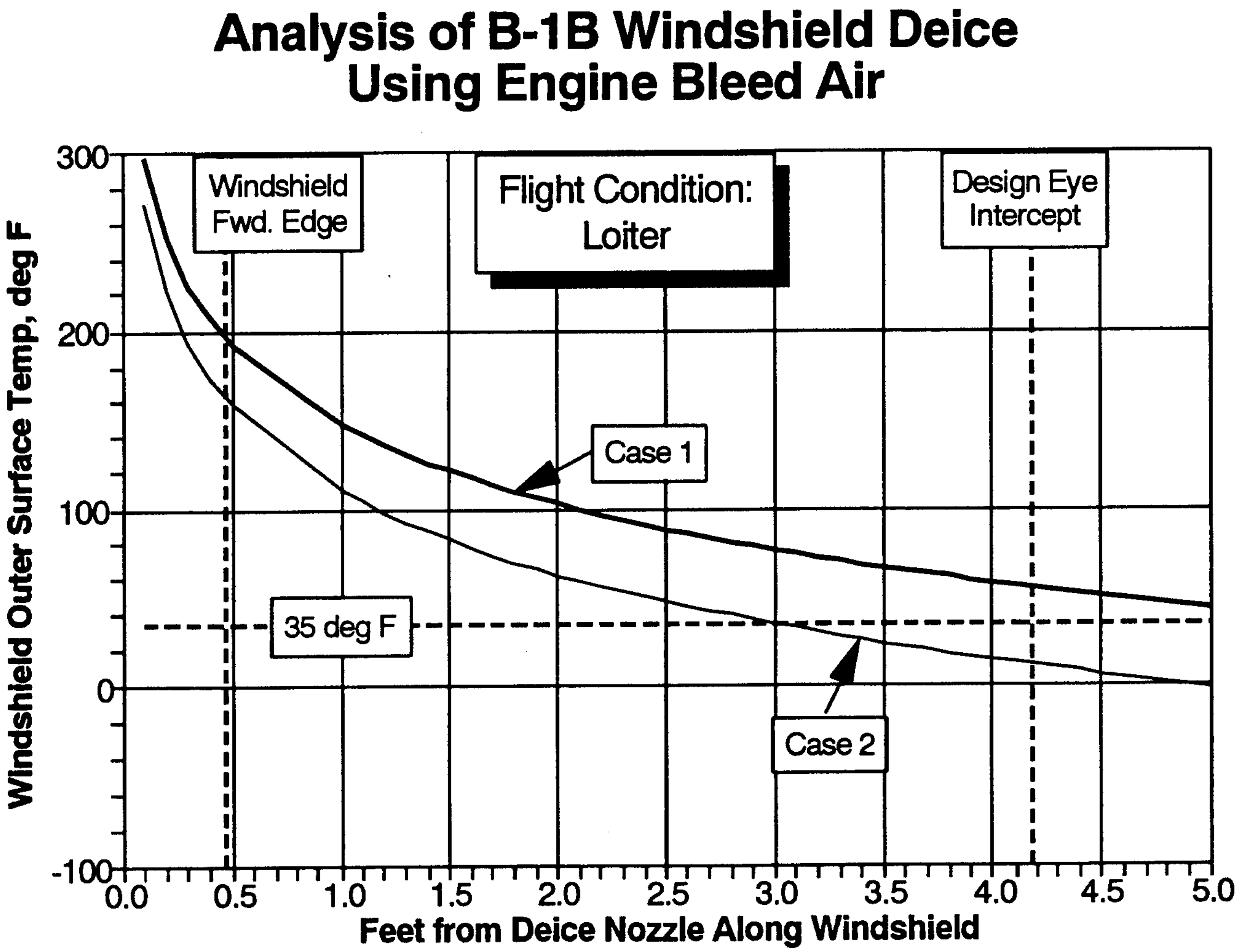

Figure 12. Windshield Outer Surface Temperature, Distribution: Loiter.

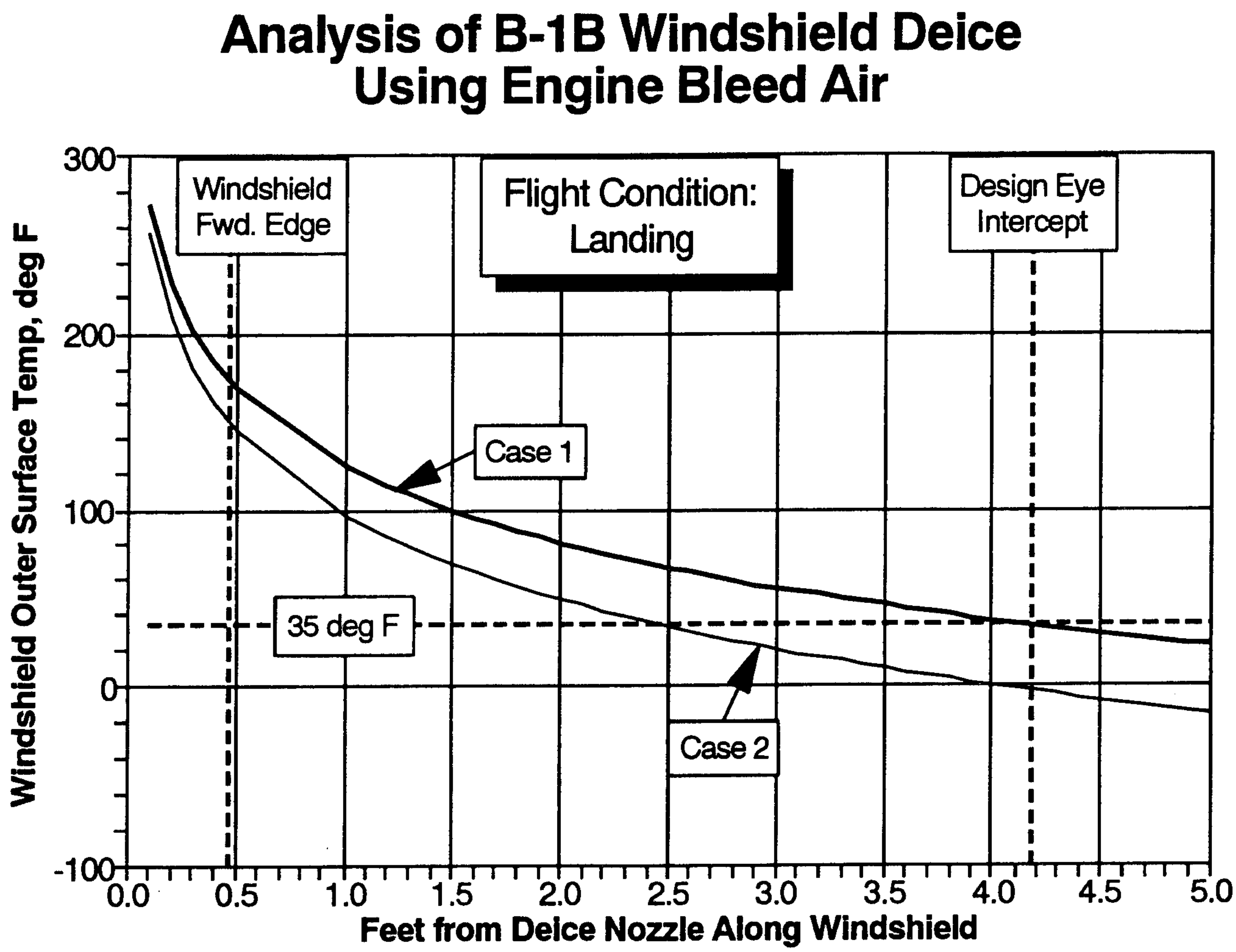

Figure 13. Windshield Outer Surface Temperature, Distribution: Landing.

SECTION 6

SUMMARY AND RECOMMENDATIONS

An analysis was conducted to determine the effectiveness of the B-1B windshield de-icing/anti-icing, external, blown-air system. The analysis assumed the blown-air system to be operating alone, without supplemental heat provided by the embedded electrical resistance system. The results of the analysis indicated that for the loiter and landing modes, the system performance ranges from marginal to adequate. It was determined that the empirically-derived equation used for analysis had not been validated for ground/taxi conditions, therefore, no results or conclusions for ground/taxi operation are presented.

It is recommended that a ground/taxi icing test be conducted to evaluate the effectiveness of the deice system to ground/taxi conditions similar to those suggested. This test could be accomplished either in an adequately equipped icing wind tunnel or on an operational aircraft under ground icing conditions. Sufficient thermocouple data should be obtained to provide input to the Ross model to extrapolate/expand its applicability into the ground/taxi regime. Similar testing should also be conducted for flight conditions in order to verify the results reported in Section 5.

REFERENCES

1. Aircraft Icing Handbook, Vol.3, Chapter V, Section 9, DOT/FAA/CT-88/8-3, March 1991.

2. Bockstahler, A.J., Meis, C.S., "Volume II - Environmental Protection System - A/C-1 and A/C-9," NA-86-1000, Vol. II, 14 January 1986.

3. CP2569A01A "Prime Item Development Specification (U) for B-1B Strategic Aircraft (U)," 23 November 1981.

4. Aircraft Icing Handbook, Vol.2, Chapter III, Section 5, DOT/FAA/CT-88/8-2, March 1991.

5. Hacker, P.T. and Dorsch, R.G., "A Summary of Meteorological Conditions Associated with Aircraft Icing and a Proposed Method of Selecting Design Criterions for Ice Protection Equipment," NACA TN 2569, 1951.

6. Aircraft Icing Handbook, Vol. 3, Chapter VI, Section 1, DOT/FAA/CT-88/8-3, March 1991.

7. Lewis, W., Kline, D.B., and Steinmetz, C.P., "A Further Investigation of the Meteorological Conditions Conducive to Aircraft Icing," NACA TN 1424, 1947.

8. Air Worthiness Standards: Transport Category Airplanes, Federal Aviation Regulations, FAR Part 25, U.S. Department of Transportation, FAA, Washington D.C., 1986.

9. Ross, R., "Analysis of an Airplane Windshield Anti-Icing System Using Hot-Air," Journal of Aircraft, Vol. 20, No. 11, November 1983.

10. "Transparent Areas on Aircraft Surfaces (Windshields and Canopies), Rain Removing and Washing Systems for Defrosting, De-Icing, Defogging; General Specifications for, MIL-T-5842B," 29 March 1985.